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IDENTIFICATION OF EARTHQUAKES AND UNDERGROUND EXPLOSIONS

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Eugene Herrin

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13. ABSTRACT

During the period January 1970 through August 1970 long period seismographs were operated at the Grand Saline Salt Mine in North-Central Texas. This report concentrates on the following tasks as outlined in the original statement of work:

a. Obtain digital data, in a standard format, of long period signals and noise and to store and make available copies of this data to other users on request.

b. Investigate methods of filtering which can be used to improve signal to noise ratios.

c. Study regional variations in frequency dependent absorption of long period surface waves. Investigate the potential effect of such regional variations on the estimation of surface wave magnitude and on the estimation of the spectral distribution of surface wave energy.

Key words:

Digital data
Long period
Grand Saline Salt Mine

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INTRODUCTION

During the period January 1970 through August 1970, long period seismographs were operated at the Grand Saline Salt Mine in North-Central Texas under AFOSR contract number 71-2133. Sponsored by ARPA Order No. 1827. This report concentrates on the following tasks as outlined in the original statement of work:

1. Obtain digital data, in a standard format, of long period signals and noise and to store and make available copies of this data to other users on request.
2. Investigate methods of filtering which can be used to improve signal to noise ratios.
3. Study regional variations in frequency dependent absorption of long period surface waves. Investigate the potential effect of such regional variations on the estimation of surface wave magnitude and on the estimation of the spectral distribution of surface wave energy.

The seismographs were of the advanced long period type with a peak response at 50 seconds. One three component system was placed at the surface and one at a depth of approximately 180 m in the mine. The seismometers were sealed in such a manner that any "noise" signal could definitely be shown to be due to ground motion and not to the buoyant response of the seismometer.

DATA ANALYSIS

Time series of 500 earthquakes selected from NOAA PDE Listings, were stripped from the Grand Saline field tapes and plotted. These events are catalogued and stored on a master library tape, readily available for such digital processing as filtering or spectral analysis.

Analysis of the Grand Saline data has shown that significant amounts of long period Rayleigh wave energy were recorded from earthquakes all over the world, with the exception of those propagated along paths through the Basin and Range Province of North America. Examples are shown in Figures 1 through 15. Figures 1, 2, and 3 show in each case signals from earthquakes that were recorded at our Grand Saline site and the same signals recorded at a site at Queen Creek, Arizona. Gains are equalized at 30 seconds in Figure 1 and at 50 seconds in Figures 2 and 3. Figure 1 displays a small earthquake from the South Pacific. Note that with the exception of the superimposed long period noise these signals are very similar. Both stations lie approximately on the same great circle arc through the epicenter; thus, the travel path to both stations is nearly identical. Figure 2 shows an earthquake from the mid-Atlantic, again approximately on a great circle arc through the recording stations. In this case, however, the waves travelled from the East. It is clearly evident that the record made at Grand Saline shows greater development of the long period surface waves. Figure 3 shows an earthquake north of Greenland recorded at the Texas and Arizona sites. The waves recorded at Grand Saline came essentially through the mid-continent region of the United States while the waves that came to the station in Arizona crossed the mountainous region of

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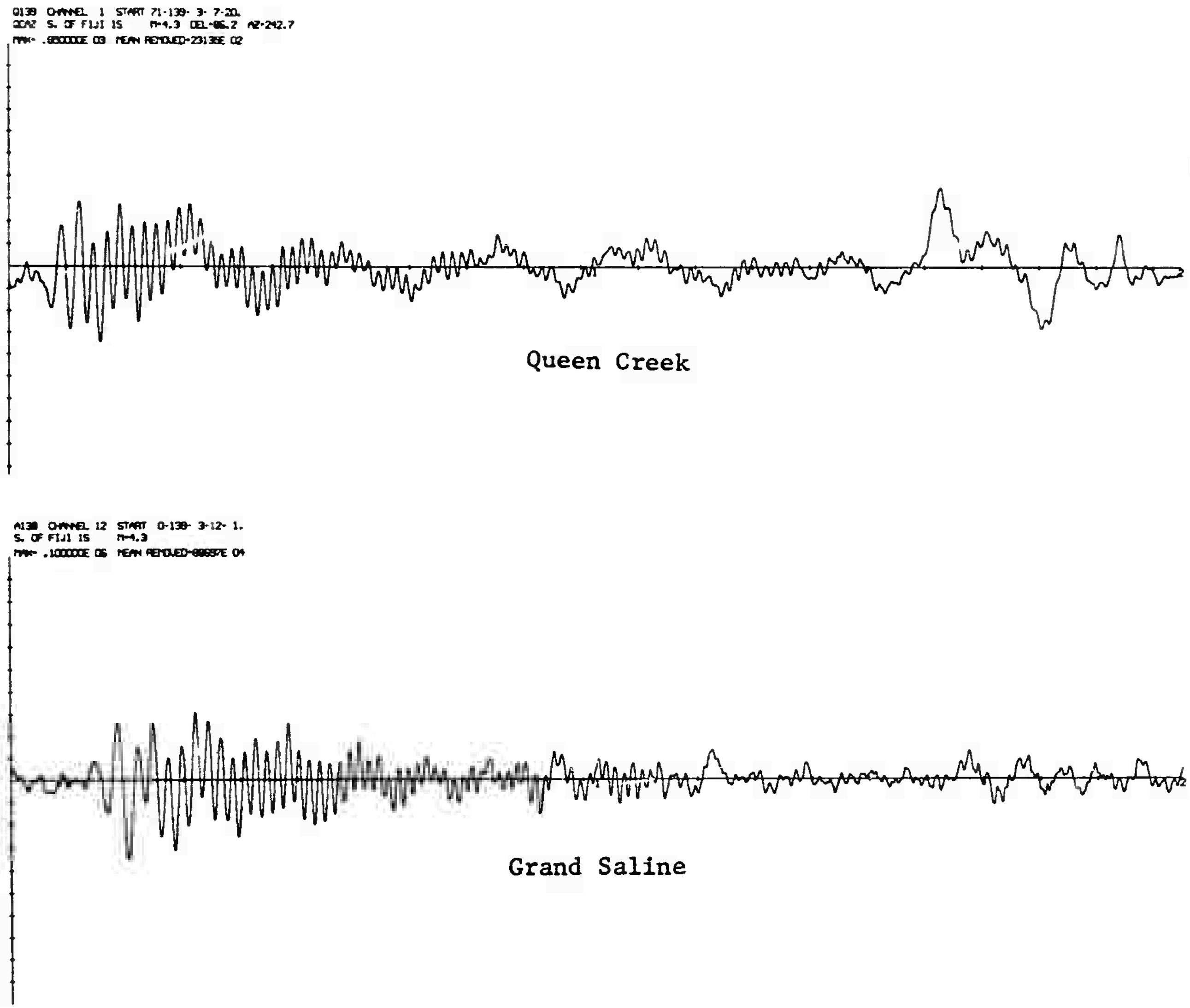
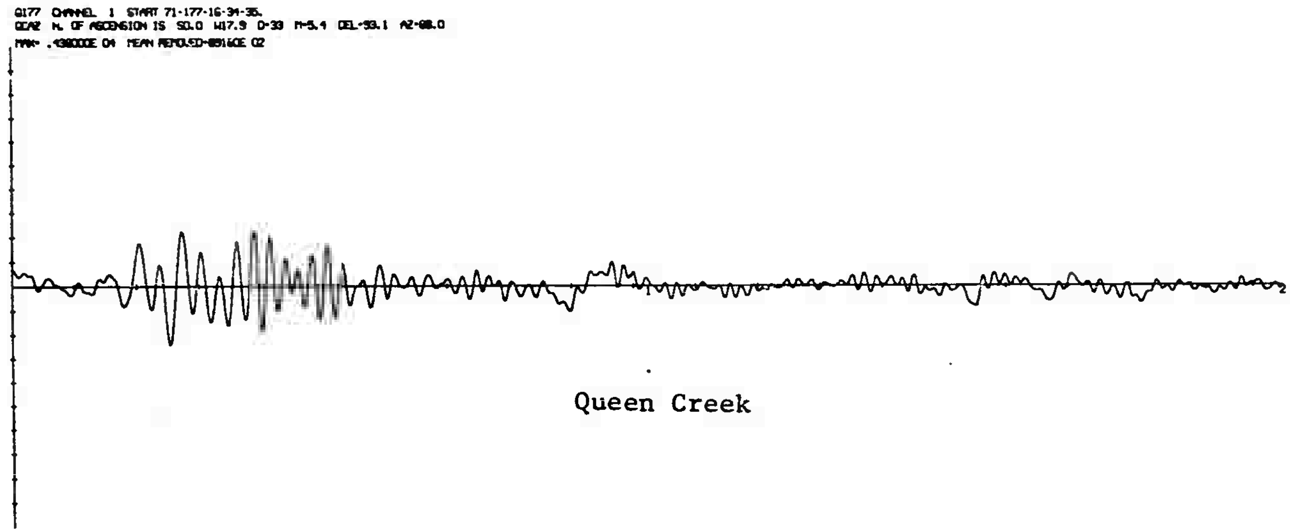
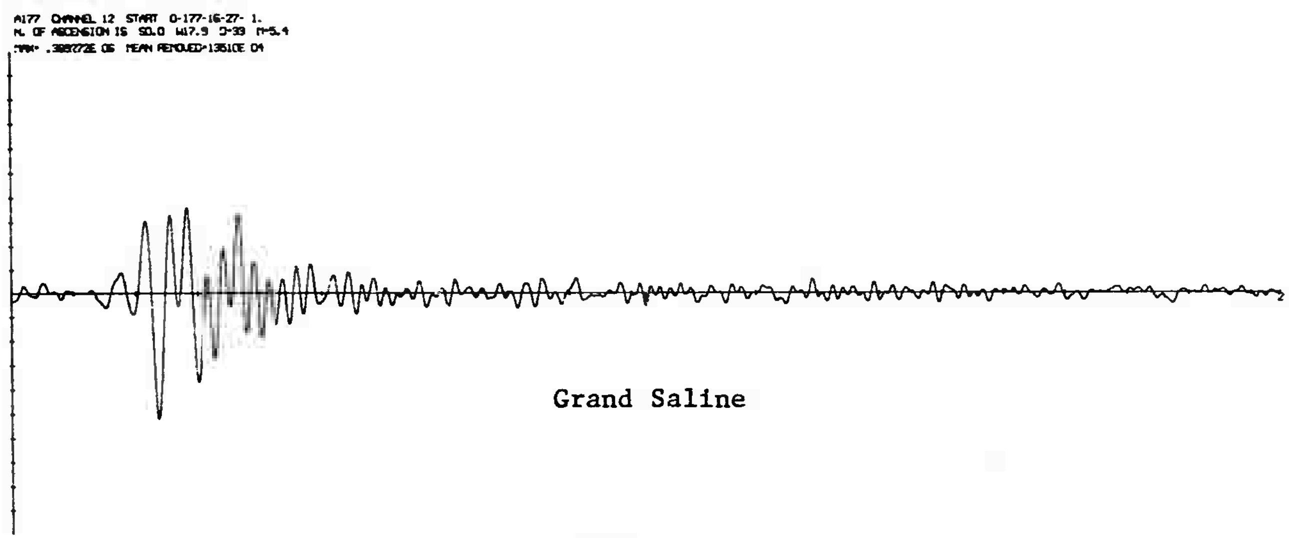

CHANNEL 1 START 71-139- 3- 7-20.
S. OF FIJI IS M=4.3 AZ=242.7
Queen Creek
A138 CHANNEL 12 START 0-138- 3-12- 1.
S. OF FIJI IS M=4.3
MAX= .100000E 06 MEAN REMOVED
Grand Saline

Figure 1



Queen Creek



Grand Saline

Figure 2

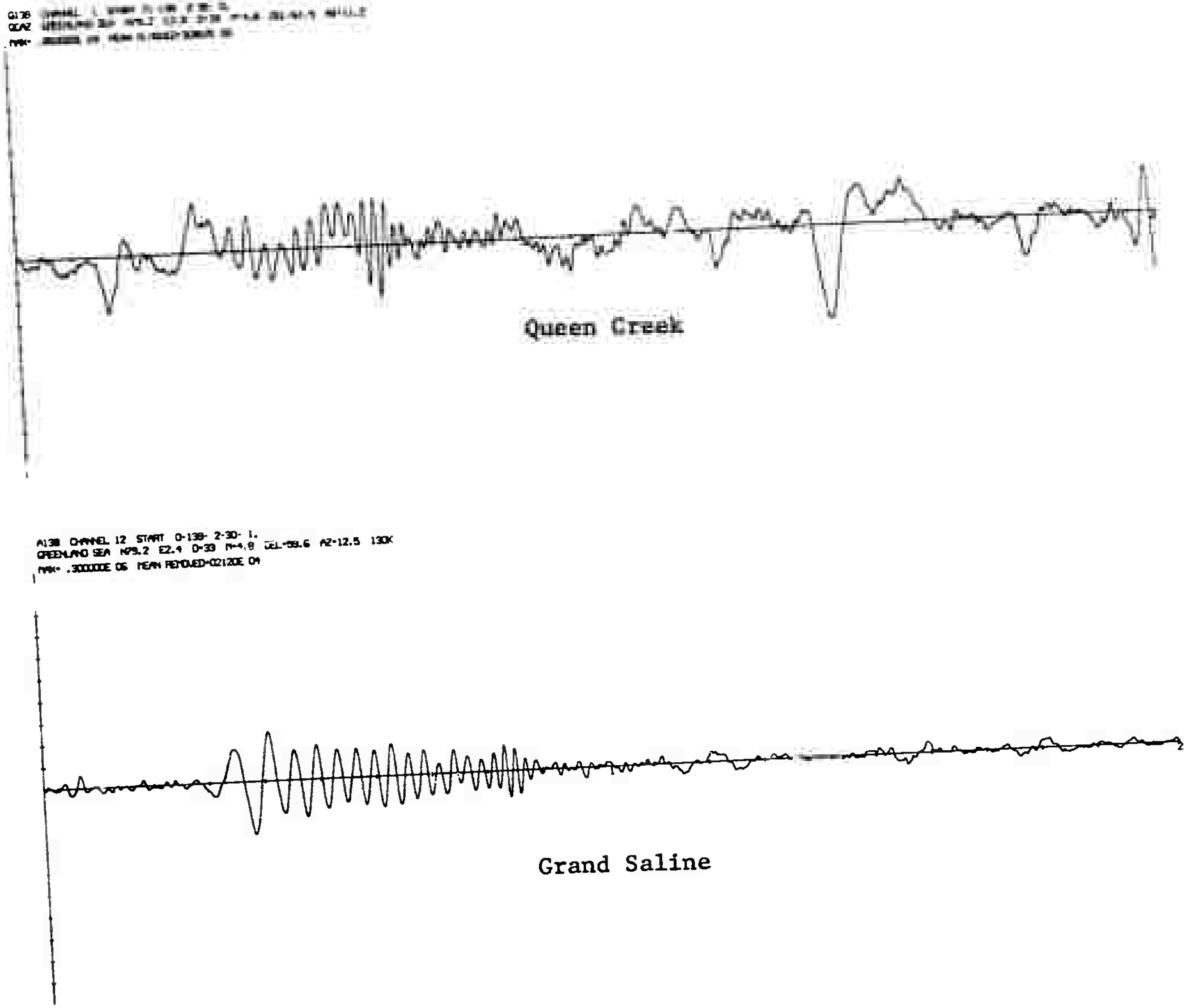

A138 CHANNEL 12 START 0-139- 2-30- 1.
GREENLAND SEA N79.2 E2.4 D-33 M-4.8 DEL-59.6 AZ-12.5 130K
MAX- .300000E 06 MEAN REMOVED-02120E 04
Queen Creek
Grand Saline

Figure 3

the western United States. Note that the longer period waves are much smaller in the Arizona recording. Figures 4 through 15 are earthquakes which all have a travel path from epicenter through the Mid-Continent region of the United States to Grand Saline. These figures show the very long period waves recorded at this station.

<u>Fig. 4</u> mb 4.4, Ms 4.1 normal depth, distance 58^o, source <u>north of Svalbard</u>, on an azimuth from Novaya Zemlya to North-central Texas. The initial Rayleigh wave arrival has a period of about 65 seconds. Note the dispersed wave train from the group velocity maximum at about 70 seconds to the minimum (Airy phase) at about 15 seconds.[1]

<u>Fig. 5</u> mb 4.3, Ms 3.5 normal depth, distance 55^o, <u>Iceland</u>, an optimum path (approximately the same azimuth as that from Semipalatinsk to North-central Texas). First arriving Rayleigh wave has a period of greater than 60 seconds.

<u>Fig. 6</u> mb 5.2, Ms 5.4, depth 13 km, distance 121^o, Sinkiang, note the pulse-like beginning at about 70 sec. This event has an unusually large Rayleigh wave.

<u>Fig. 7</u> <u>Energy density spectrum</u>, of the <u>Sinkiang</u> event shown in Fig. 6. This and the following spectrum are <u>not</u> corrected for instrument response. Note the significant energy at about 60-70 sec. and the spectral notch at about 20 sec.

1. All hypocentral information and body wave magnitudes in this and following discussion are from NOAA. Ms was calculated from Grand Saline records.

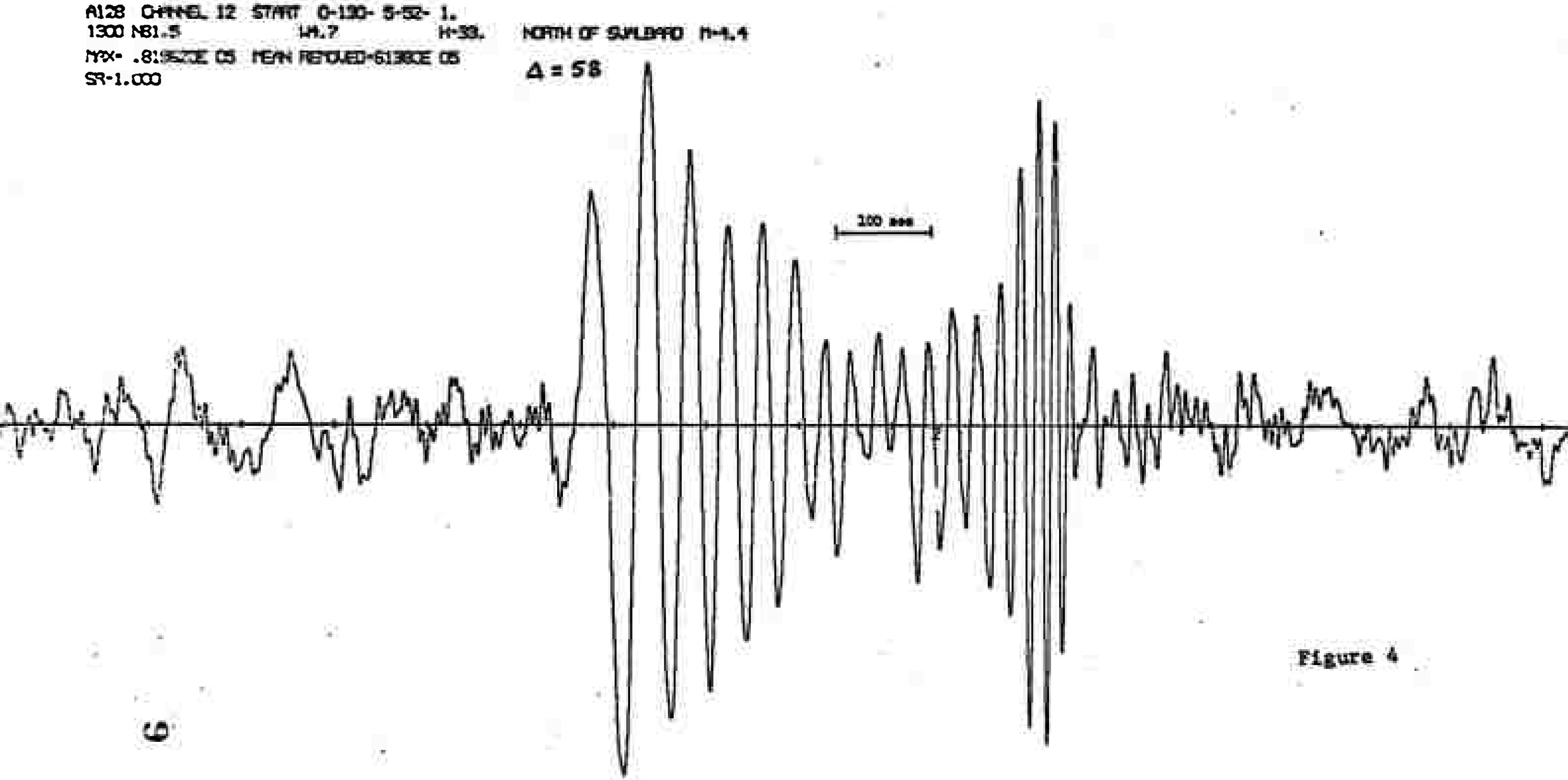

A128 CHANNEL 12 START 0-130- 5-52- 1.
1300 N81.5 W4.7 H-33. NORTH OF SVALBARD M=4.4
SR=1.000
Δ = 58
100 sec

Figure 4

A180 CHANNEL 12 START 0-181- 3-39- 0.
1810 N68.0 W16.7 H-35. ICELAND REGION M-4.3
MAX- .662132E 05 MEAN REMOVED-13972E 05 $\Delta = 55$
SR-1.000

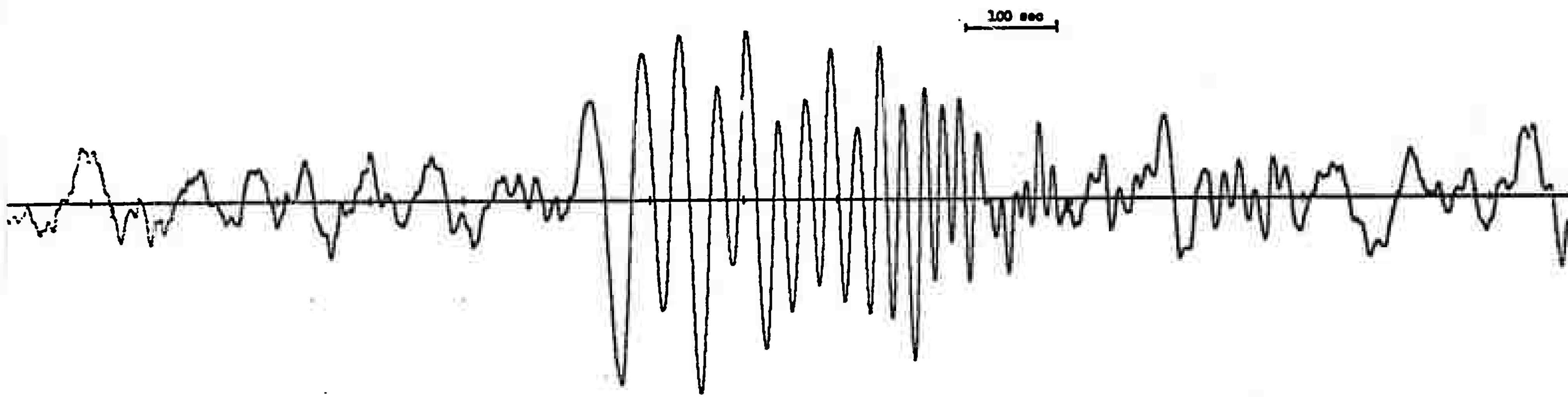


Figure 5

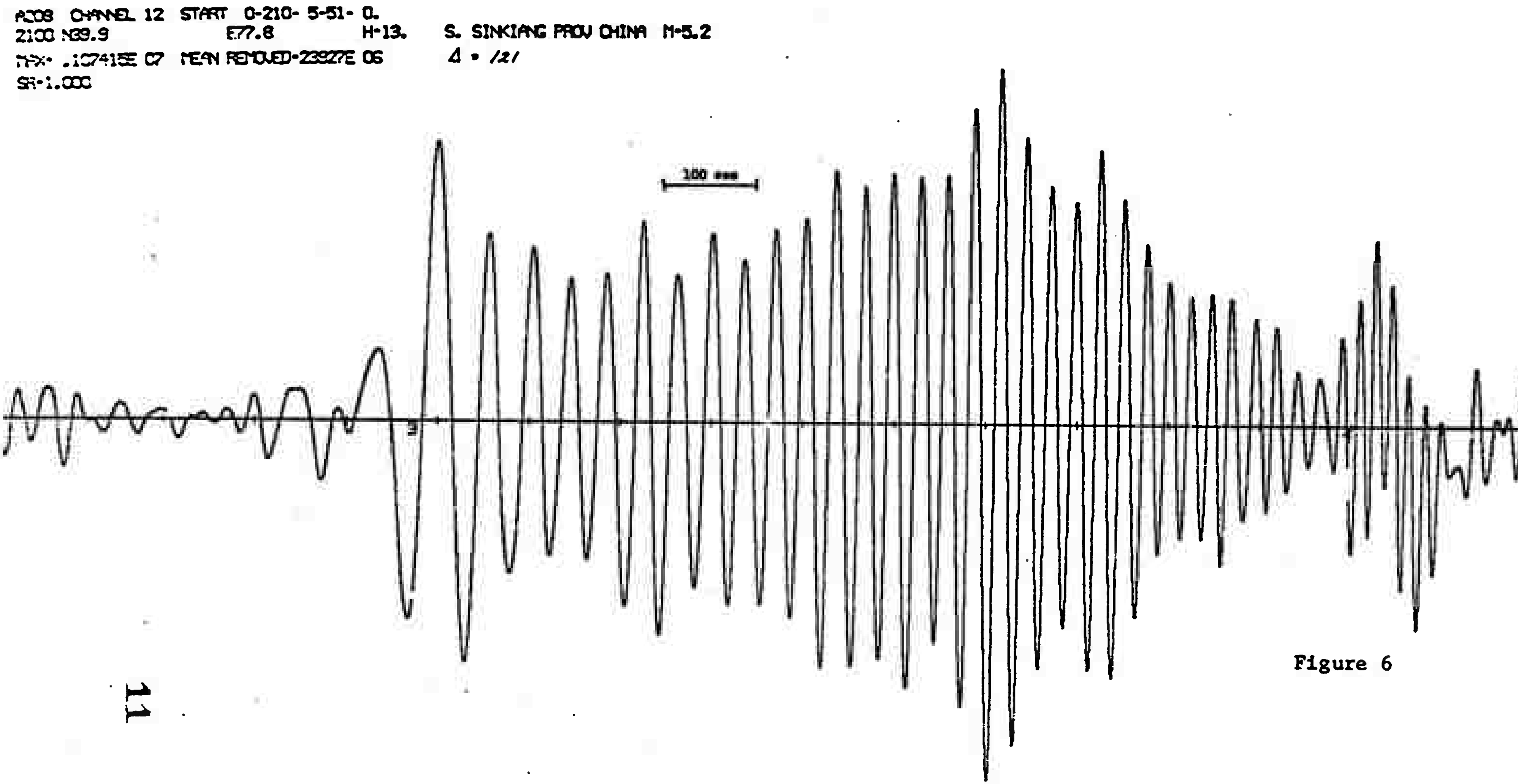

A208 CHANNEL 12 START 0-210- 5-51- 0.
2100 N39.9 E77.8 H-13. S. SINKIANG PROV CHINA M-5.2
MAX- .107415E 07 MEAN REMOVED-23927E 05 Δ = 121
SR-1.000
100 sec

Figure 6

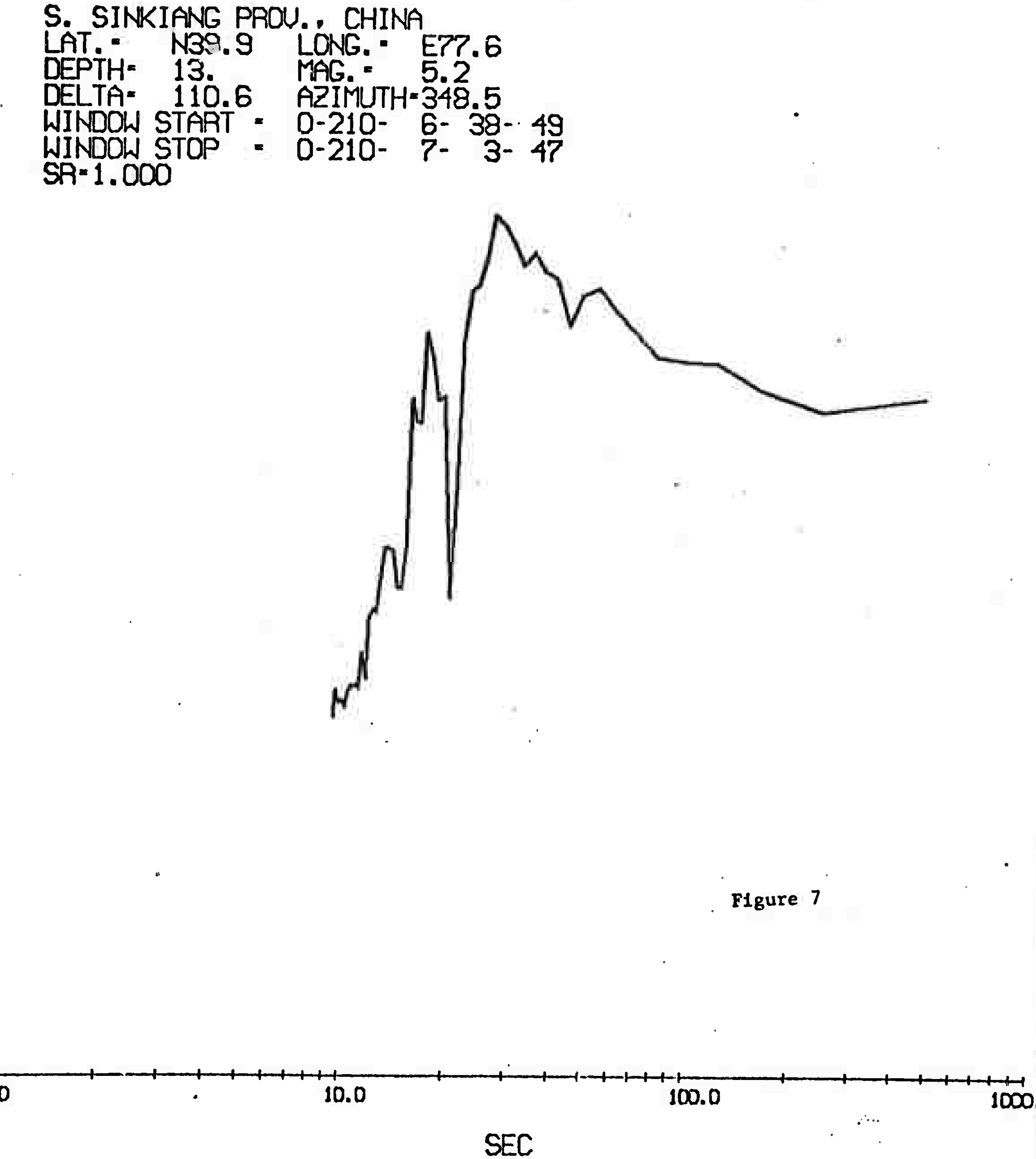

S. SINKIANG PROV., CHINA
LAT.= N39.9 LONG.= E77.6
DEPTH= 13. MAG.= 5.2
DELTA= 110.6 AZIMUTH=348.5
WINDOW START = 0-210- 6- 38- 49
WINDOW STOP = 0-210- 7- 3- 47
SR=1.000
10.0
100.0
1000.
SEC

Figure 7

Fig. 8 mb 4.5, Ms 3.4, depth 43km, distance 97°, USSR-Mongolia border, data was high-pass filtered with corner at 50 sec. to enhance detection. Starting period is greater than 40 sec.

Fig. 9 mb 4.4, Ms 3.4, depth normal, distance 97°, Caucasus high-pass filtered as for Fig. 8. This event is very near threshold for single LP vertical instrument at Grand Saline. First periods observed are 30 to 40 sec.

Fig.10 Energy density spectrum, mb 5.0, Ms 4.2, Caucasus. This figure shows the spectrum for a larger event from the same source area as for Fig. 9. The spectral content, with significant energy to periods of 60 sec. seems to be typical of this source area.

Fig.11 mb 4.5, Ms 3.5, depth 25 km, distance 85°, Albania. The record is underlined where the Rayleigh wave was predicted to arrive. The first observed period is about 50 sec.

Fig.12 mb 4.9, Ms 3.9, depth normal, distance 121°, Yunnan, China, starting period is greater than 40 sec.

Fig.13 mb 4.9, Ms 4.5, depth normal, distance 86°, Lake Baikal region. This event is mixed with the tail of a Rayleigh wave which arrived 50 min. earlier from Mongolia (mb 5.0).

Fig.14 mb 4.7, Ms 3.7, depth normal, distance 70°, Kamchatka. The surface wave travelled a rather poor path through the Aleutian arc and northwestern Canada. The starting period is about 60 sec.

Fig.15 mb 4.9, Ms 3.5, focal depth near 100 km, distance 114°, Taiwan region. The first arriving Rayleigh waves have periods of 70 to 75 seconds. Note the pulse-like appearance of the Rayleigh wave train and the relatively low amplitude of the shorter period components

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A142 CHANNEL 12 START 0-143-14-51- 1.
143 N50.1 E91.6 43. MB-4.5 MS-3.4 DELTA- 97. USSR MONGOLIA BOR.
MAX- .162910E 05 MEAN REMOVED-83026E 02
SR-1.000

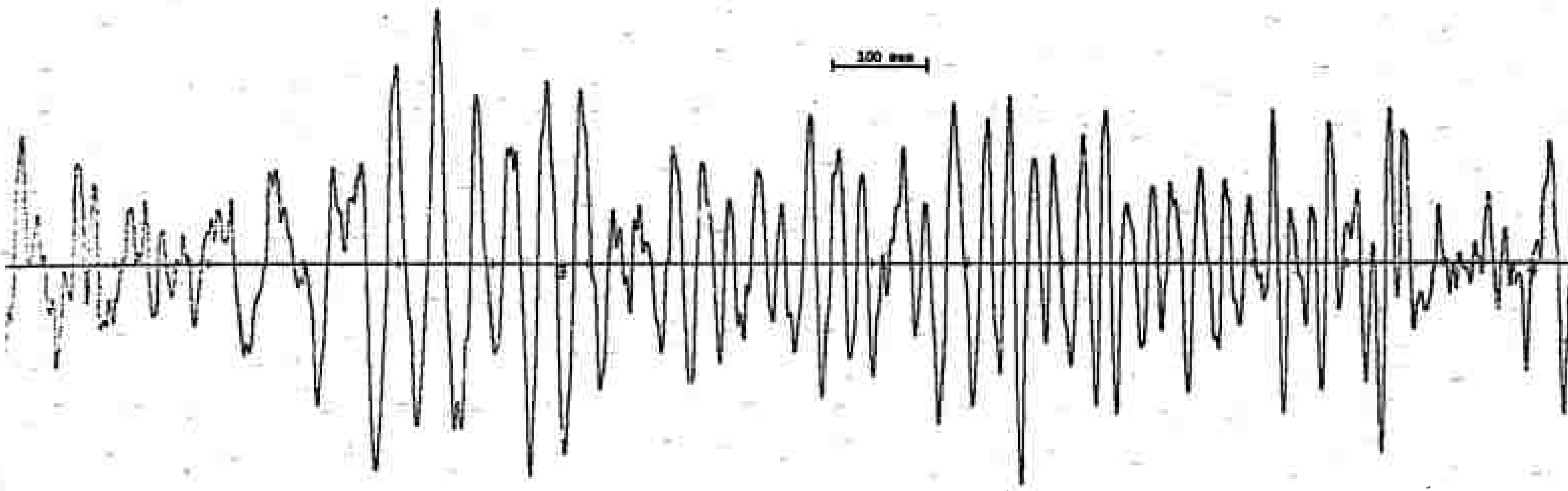


Figure 8

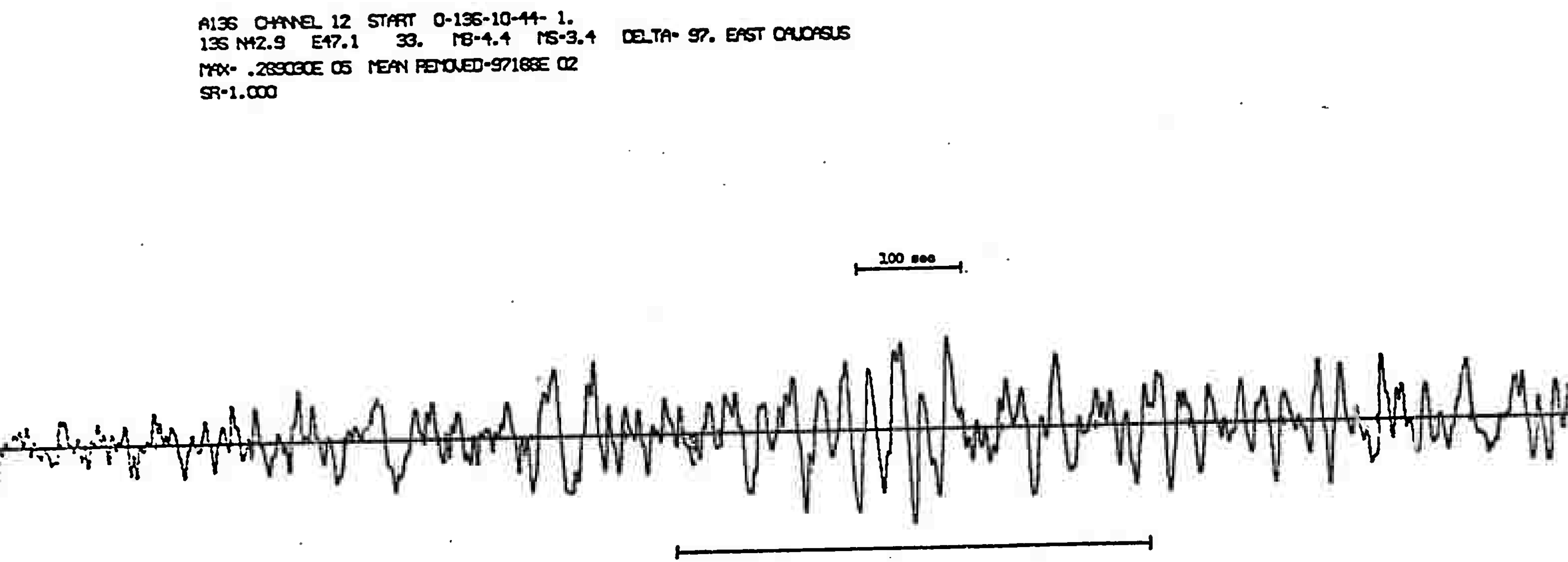

A136 CHANNEL 12 START 0-136-10-44- 1.
135 N42.9 E47.1 33. MB-4.4 MS-3.4 DELTA- 97. EAST CAUCASUS
MAX- .289030E 05 MEAN REMOVED-97183E 02
SR-1.000
100 sec

Figure 9

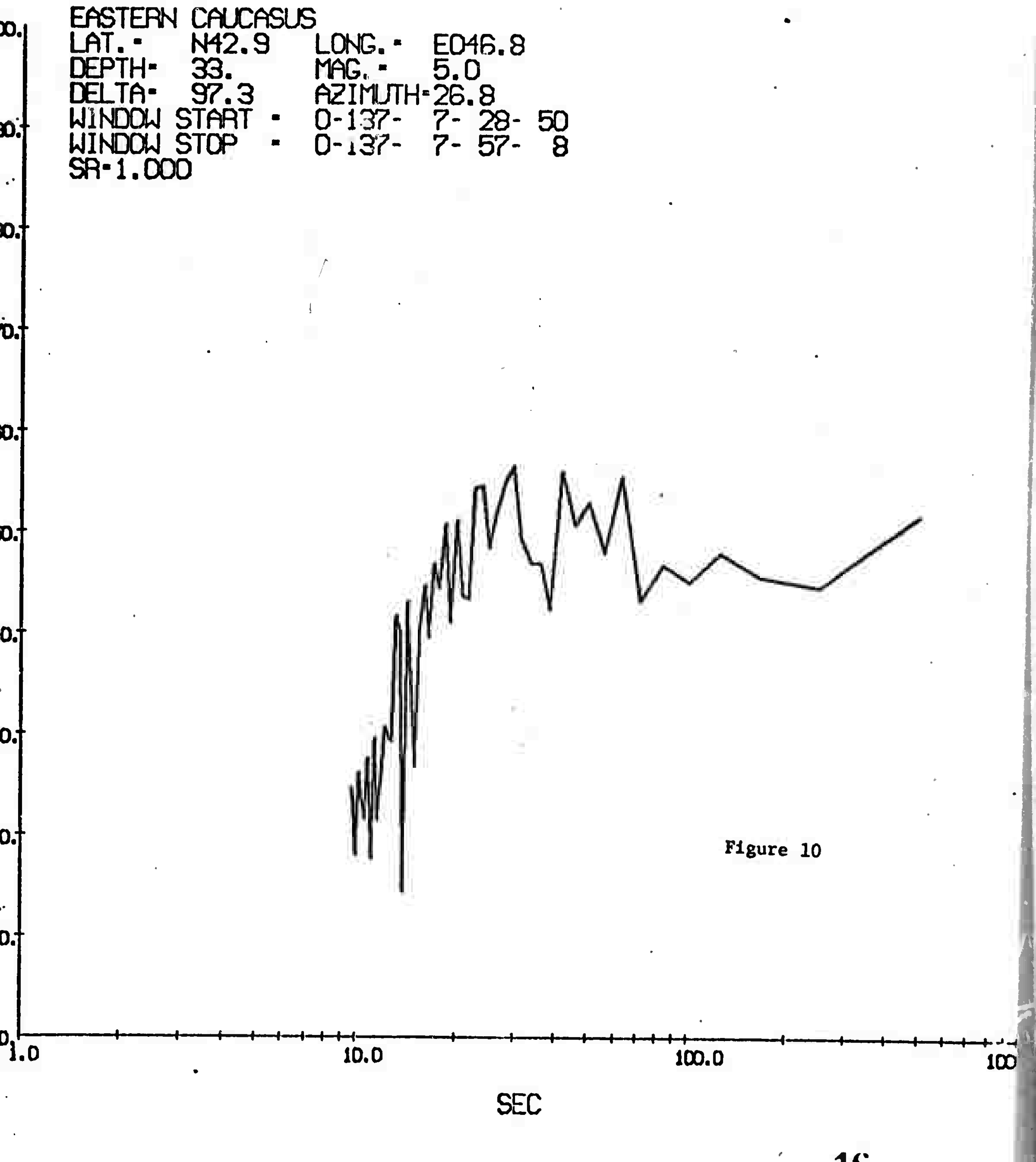

EASTERN CAUCASUS
LAT. = N42.9 LONG. = E046.8
DEPTH = 33. MAG. = 5.0
DELTA = 97.3 AZIMUTH = 26.8
WINDOW START = 0-137- 7- 28- 50
WINDOW STOP = 0-137- 7- 57- 8
SR = 1.000
1.0
10.0
100.0
SEC

Figure 10

A177 CHANNEL 12 START 0-178-18-58- 1.
178 N41.5 E19.4 25. MB-4.5 MS-3.5 DELTA- 85. ALBANIA
MAX- .188130E 03 MEAN REMOVED-19145E 01
SR-1.000

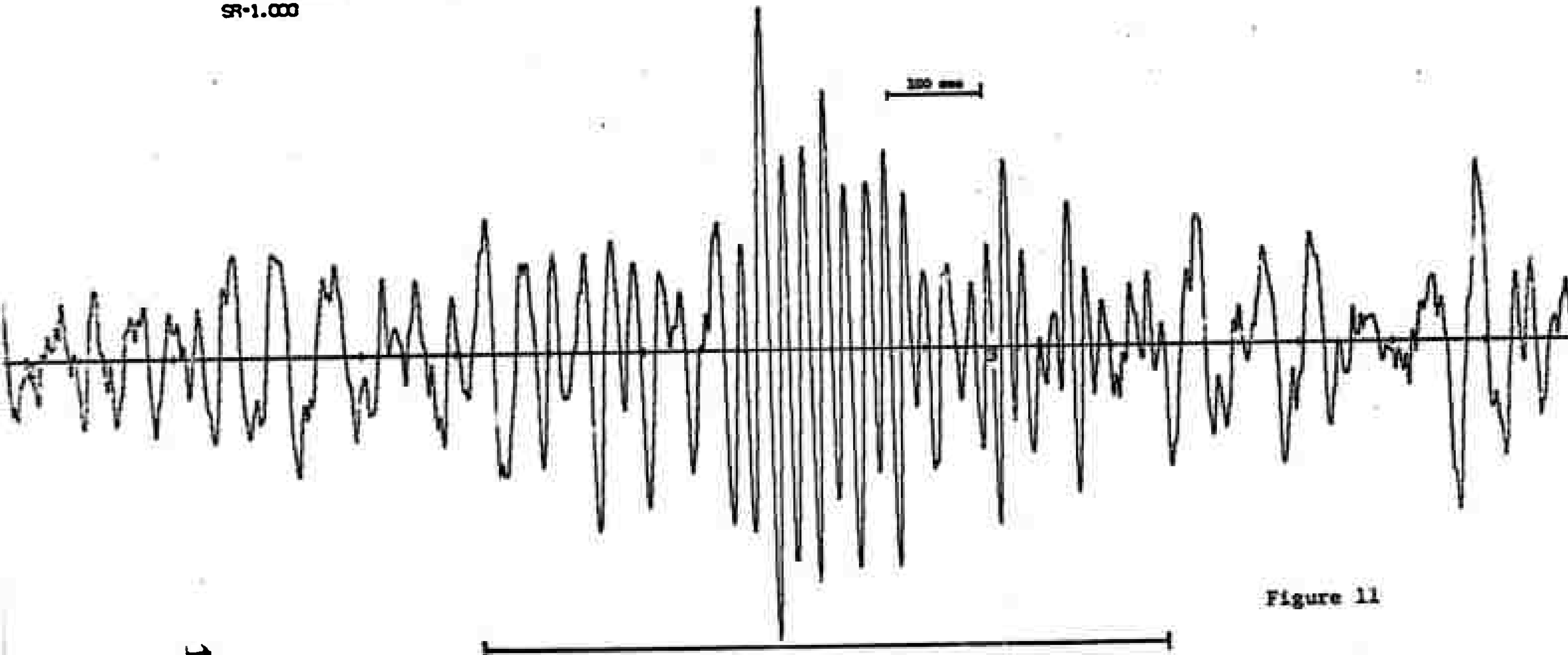


Figure 11

A167 CHANNEL 12 START 0-168-12-11- 1.
168 N24.2 E102.4 33. MB-4.8 MS-3.9 DELTA-121. YUNNAN PROVINCE, C NA
MAX- .834621E 05 MEAN REMOVED-34621E 05
SR-1.000

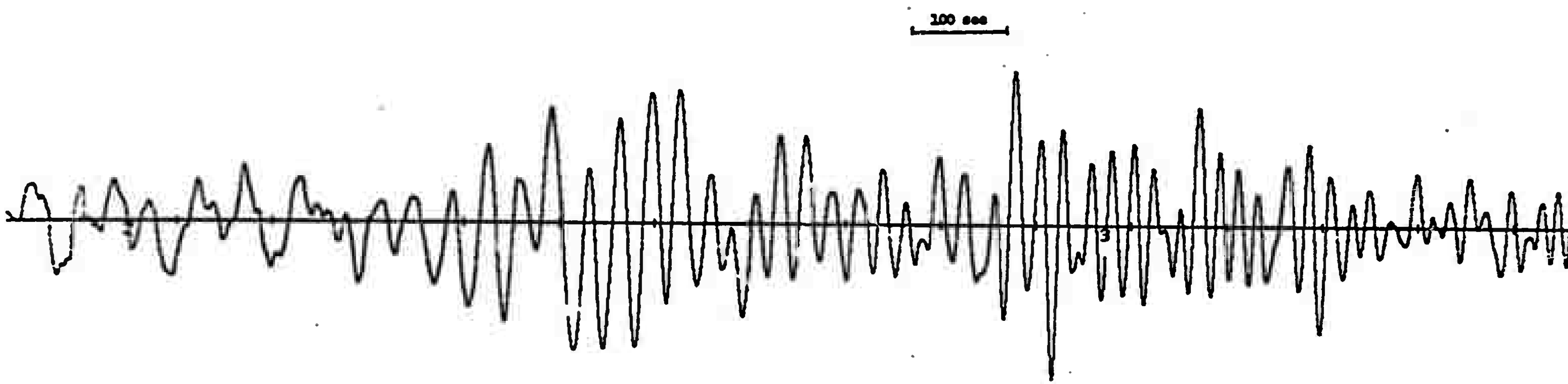


Figure 12

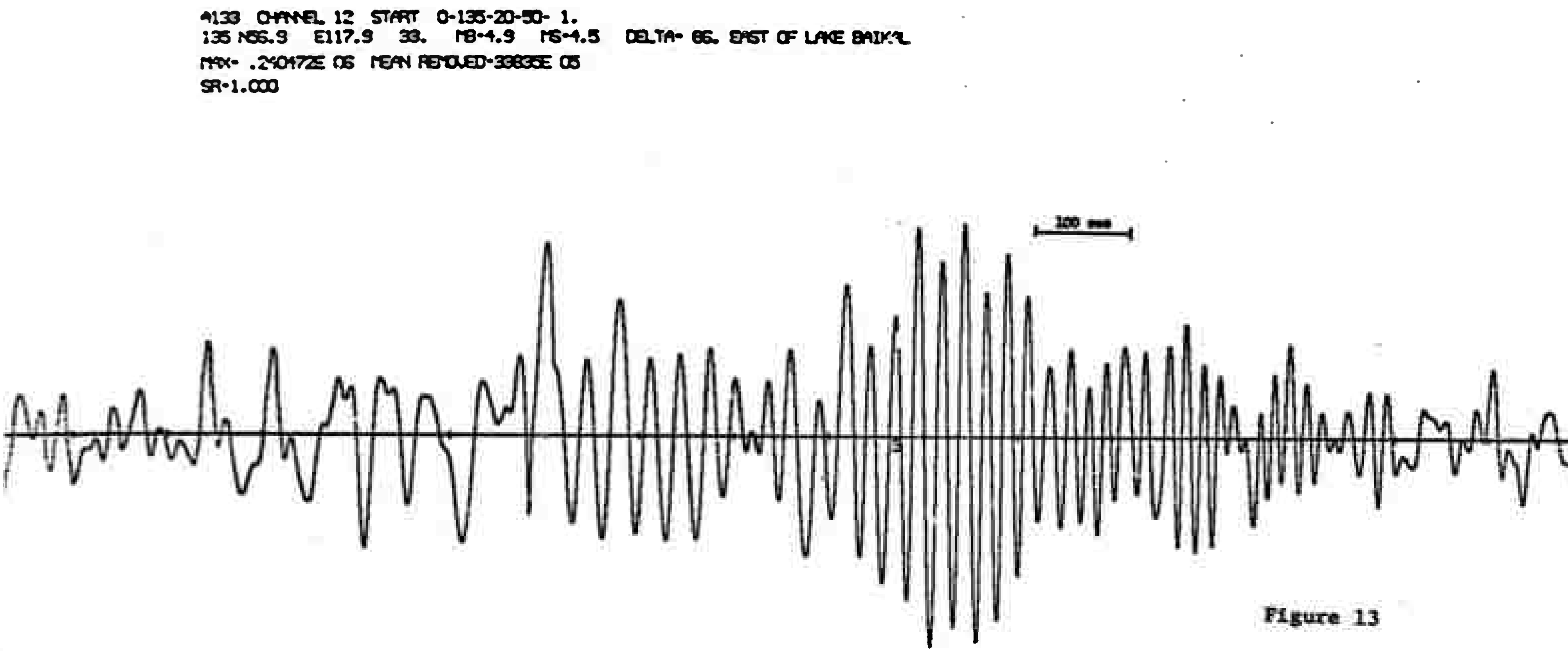

4133 CHANNEL 12 START 0-135-20-50- 1.
135 N56.3 E117.9 33. MB-4.9 MS-4.5 DELTA- 66. EAST OF LAKE BAIKAL
MAX- .240172E 06 MEAN REMOVED-33835E 05
SR-1.000
100 sec

Figure 13

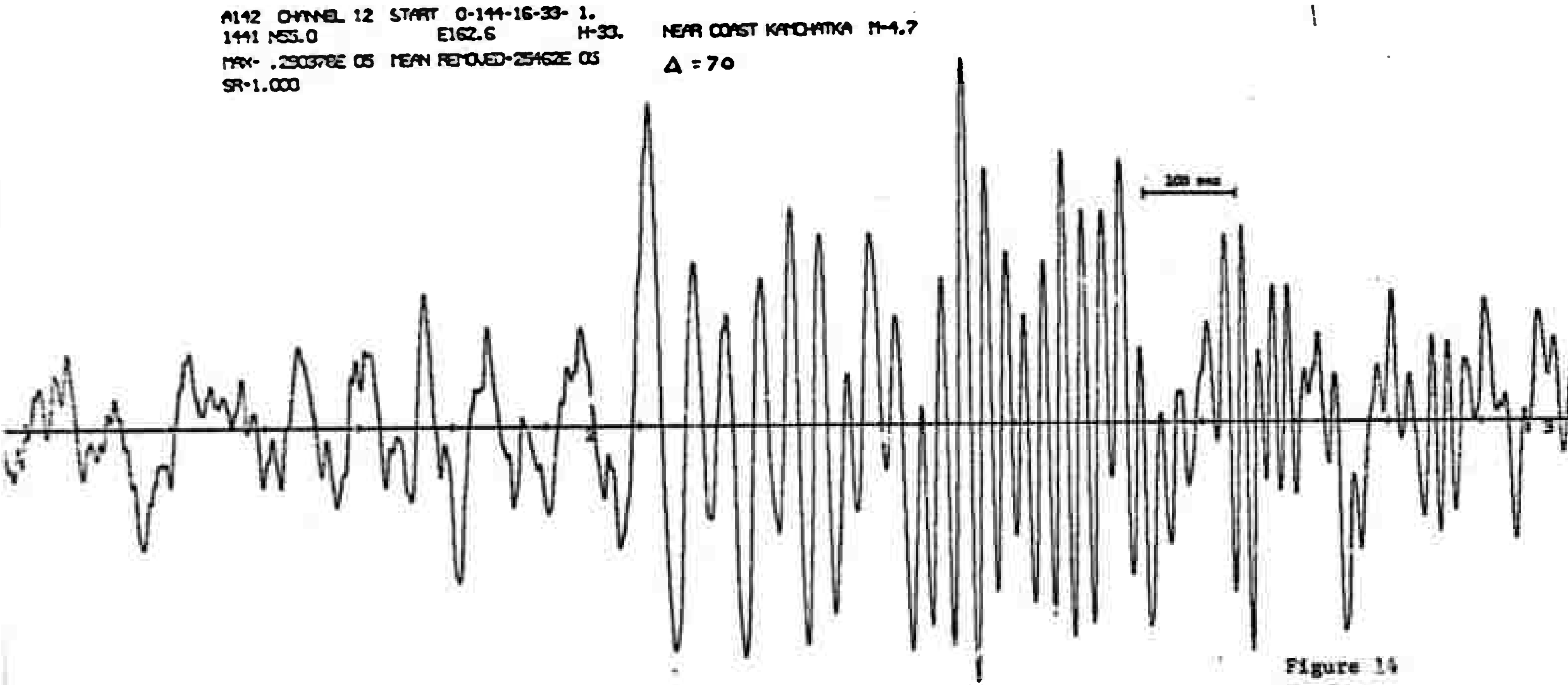
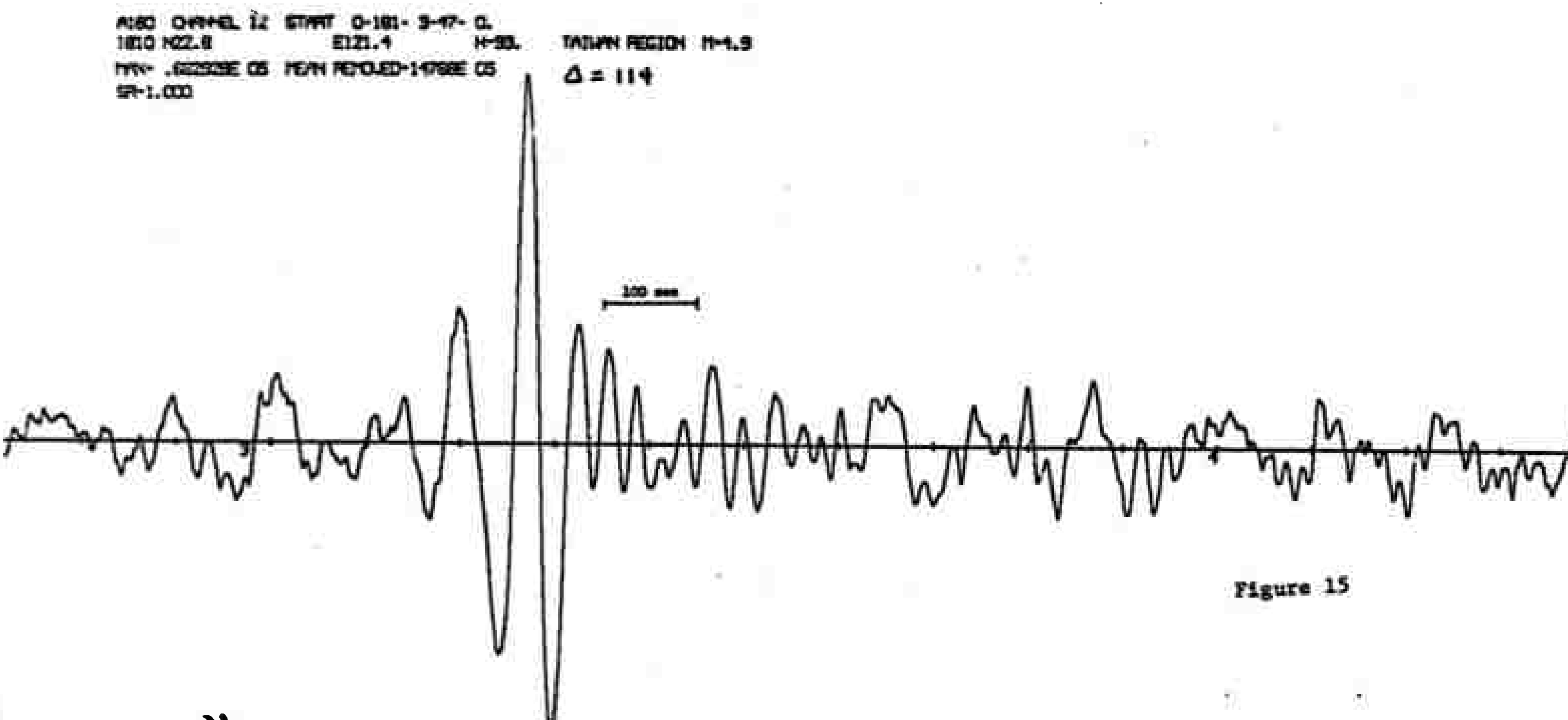

A142 CHANNEL 12 START 0-144-16-33- 1.
1441 N55.0 E162.6 H-33. NEAR COAST KAMCHATKA M-4.7
MAX- .290378E 05 MEAN REMOVED-25462E 03
SR-1.000
Δ = 70

Figure 14



CHANNEL 12 START
E121.4
TAIWAN REGION
MEAN REMOVED
SR=1.000
Δ = 114

Figure 15

(as would be expected from an earthquake with this depth of focus). Detection of this event is definitely aided by the enhanced long period response of the Grand Saline seismic system.

In each case these figures demonstrate that long period Rayleigh waves are very efficiently propagated to northcentral Texas along paths from northeast, north and northwest of the station. We feel these studies, using a single seismograph, have established that north Texas lies at the southern end of a waveguide extending from the southern borders of the USSR and northern China across the Arctic Ocean and the Canadian Shield. In the United States the waveguide is bounded on the west approximately by a line through Carlsbad and the Black Hills and on the east by the Atlantic and Gulf Coastal Plains. This waveguide is characterized by relatively low temperatures in the lower crust and upper mantle which results in an exceptionally good propagation path for Rayleigh waves with periods from 30 to 60 sec. An approximate detection threshold of Ms 3.5 has been established for a single station in North Central Texas for events in the waveguide at distances as great as 100°. Because most of the detections were made at periods greater than 40 sec., this magnitude is equivalent to about mb 4.5 for earthquakes less than 50 km in depth.

We have observed the long period "noise hole" or "window" which has been described by using data recorded at Ogdensburg, New Jersey, Queen Creek, Arizona, and Las Cruces, New Mexico. This spectral hole is shown in Figure 16 for both the seismometer in the mine and the surface seismometer (during a near calm period). It is clear that any long period seismic array should take advantage of this noise minimum for detection purposes.

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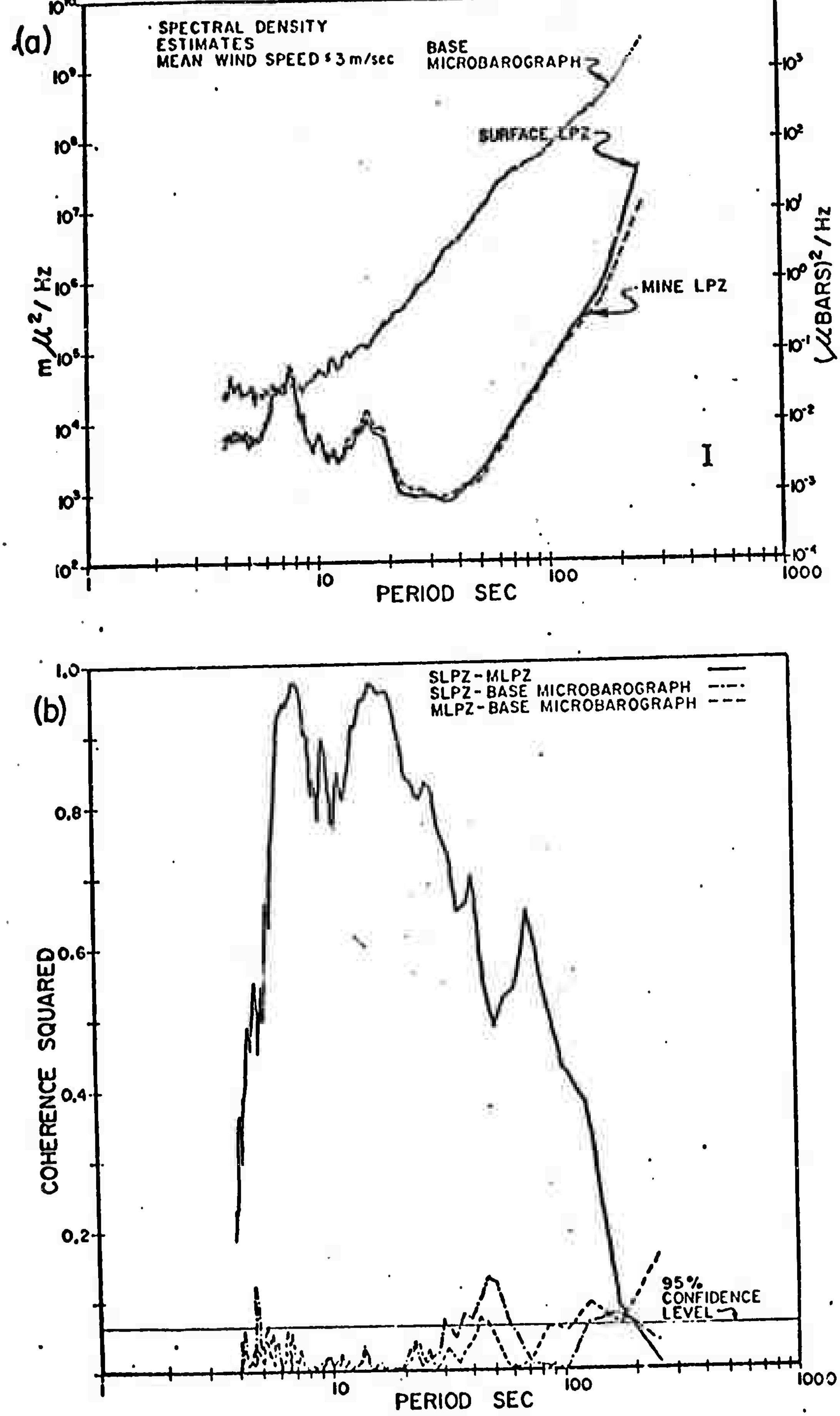
(a)
SPECTRAL DENSITY
ESTIMATES
MEAN WIND SPEED ≤ 3 m/sec
BASE
MICROBAROGRAPH
SURFACE LPZ
MINE LPZ
mμ^2/Hz
(μBARS)^2/Hz
PERIOD SEC
(b)
SLPZ-MLPZ
SLPZ-BASE MICROBAROGRAPH
MLPZ-BASE MICROBAROGRAPH
COHERENCE SQUARED
95% CONFIDENCE LEVEL
PERIOD SEC

Figure 16

To establish an earthquake detection capability for the Grand Saline site, records from the vertical long period seismograph were examined for a 30-day period during May and June, 1970. All discernible signals were listed by arrival time and period of initial Rayleigh wave motion. It was not possible to determine the location and magnitude of most of these events because they were not reported by NOAA. Table 1 shows the breakdown of the period measurements. We sould expect that close to 50% of those events having a magnitude mb 4.0 and above would be recorded at Grand Saline and of these, 80% would be detected having initial Rayleigh motion at greater than 40 sec. period.

Table 2 displays the results of an examination of Grand Saline data specifically conducted to detect events from the Sino-Soviet Region. These data indicate that the detection threshold, with relatively high confidence, for the Grand Saline station for Rayleigh waves from Sino-Soviet events is approximately Ms 3.5 (mb 4.5 for normal earthquakes).

We conclude from Table 2 and from the previously shown seismograms that there is significant Rayleigh wave energy up to periods of 60 sec. propagated along paths from the USSR and China to north-central Texas and that it is possible to exploit the "noise window" centered at about 35 seconds to improve Rayleigh-wave detection. Since most events along this waveguide have measurable energy at periods greater than 40 seconds the Rayleigh wave detection threshold would remain about the same for earthquakes as deep as 50 to 60 km. Surface wave magnitudes (M_s) reported here were measured at or near periods of 20 seconds. Magnitude measurements from Grand Saline records based on longer period Rayleigh waves may be more stable than the conventional Ms measurements because these longer periods are less affected by depth of focus and small-scale path variations.

Table 1

Detection Study

30 Days

During May and June, 1970

Single Vertical LP - Grand Saline, Texas, Mine

Longest Period Detected	Percentage of Events Detected
60-70 sec.	15%
50-60	38%
40-50	31%
30-40	8%
20-30 sec.	8%

Total number of events detected - 380

Avg. number of events/day - 12.7

Predicted number of events/year - 4623

Table 2

SUMMARY

SINO - SOVIET - EARTHQUAKES

NOAA Origin Time	Depth	Distance (in deg.)	1st Period Detected (in sec.)	NOAA M_b	G.S. M_s	Signal-to-noise ratio	Location
136 1044	33	97	35	4.4	3.4	2	E. Caucasus
137 0503	33	97	40	4.7	3.5	2	E. Caucasus
136 2127	33	97	40	4.8	3.6	3	E. Caucasus
134 0920	17	97	55	5.6	4.9	4	E. Caucasus
137 0649	33	97	55	5.0	4.2	7	E. Caucasus
134 1812	44	97	55	5.6	5.7	8	E. Caucasus
192 2242	65	103	55	5.1	4.2	6	Caspian Sea
178 1858	25	85	35	4.5	3.5	3	Albania
178 0758	14	105	55	4.9	3.5	3	Iran
211 0052	19	105	55	5.7	5.7	20	Iran - USSR
143 1451	43	97	45	4.5	3.4	2.5	USSR - Mongolia
137 0057	33	73	45	5.5	4.5	2	USSR - Mongolia
135 2012	33	97	70	5.0	4.1	3	USSR - Mongolia
135 1713	33	97	60	5.9	5.0	7	USSR - Mongolia

NOAA Origin Time	Depth	Distance (in deg.)	1st Period Detected (in sec.)	NOAA M_b	G.S. M_s	Signal-to-noise ratio	Location
135 2050	33	86	40	4.9	4.5	5	Lake Baikal
156 0454	20	105	60	6.0	5.5	20	Alma Ata
212 1310	25	116	60	5.5	4.2	3	Szehwan Prov.
210 0551	13	107	65	5.2	5.4	10	SinKiang Prov.
168 1151	33	121	45	4.8	3.9	2	Yunnan Prov.
156 1031	33	73	45	5.5	4.5	6	E. Siberia
144 1633	33	70	55	4.7	3.7	3	E. Kamchatka

EFFECTS OF DEPTH OF FOCUS

Theory based on seismic sources in a layered half-space gives predictions of the effect of source depth on the spectra of resulting Rayleigh waves. In general, we expect the spectral energy to shift, in a relative sense, toward the longer periods as the source depth is increased. Details of the spectral shape depend in a complicated way upon the nature of the source, propagation azimuth relative to source symmetry, the physical properties of the layering, and the exact depth of focus.

Our studies of Rayleigh wave spectra obtained from the Grand Saline data show that for many earthquakes in the Pacific island arc regions (e.g., Tonga Islands), there is no discernable shift in spectral energy with increasing depth of focus. Shorter period Rayleigh wave energy is generated just as efficiently by sources at 250 km as by those 20 km deep. The theory, based on a layered half-space, is clearly not applicable to these island arc regions, which are the source areas of about 90% of all earthquakes. A more realistic Earth model, in which a downgoing slab of lithosphere is considered, greatly complicates the theoretical problem. Numerical solutions to the laterally-heterogeneous problem are possible in principle, but would be difficult and time consuming in practice.

As a first approach to this problem we intend to design and construct two-dimensional analog models of an assumed island arc source region with a downgoing slab. The models will be scaled such that Rayleigh wave energy will be in the range 20 to 200 kilocycles. Sampling techniques will be employed to obtain

seismic records and to convert the signals into digital form for storage on magnetic tape. The model signals can then be processed in exactly the same way as the data from the long period seismographs.

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Canton Experiment

The success of the Grand Saline experiments led to the installation of a long period triaxial seismometer in a 300 m borehole at a site near Canton. This seismograph system was again operated in conjunction with a 3-component system at the surface and with tripartrite 5 km microbarograph array. The borehole enabled the seismometer to be clamped at different depths. This site was in operation for the period February 1971 through May 1972.

During this operating period the TC-200 Data Acquisition System was recording for 78% of the time. Most down time can be accounted to power failures with the rest under the categories of maintenance and tape changes.

Preliminary analysis of approximately 100 selected events recorded at the Canton site bear out the findings in the Data Analysis Section of this report. We are currently in the process of selecting events and updating our event library tapes as with the Grand Saline data. Fourier analyzing will be accomplished for all Rayleigh wave signals which have a sufficiently large signal-to-noise ratio. The spectral information is also stored on a library tape for subsequent processing.

Digital recording of seismic data and subsequent digital processing techniques developed at Southern Methodist University enabled us to support the LRSM group at Canton (Teledyne Geotech) in their studies of noise sources of the down-hole, triaxial long period seismometer. These same techniques along with microbarograph data from our existing infrasonic research program supported Dr. G. (Mike) Sorrells (Teledyne Geotech) in his continuing measurements of long period atmospheric and seismic background noise, in order to investigate the causes of the seismic background noise and perhaps to develop methods to minimize that noise.

3^

Future Studies

Data from the Grand Saline and Canton experiments support the existence of a polar wave guide for long period Rayleigh waves. A third experiment, designed to collect still more long period data, is being planned for a site about 35 miles north of Dallas. At this site we will investigate the possible use of information from a multi-element microbarograph array to predict and possibly reduce long period seismic background noise.